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Optimization schemes for grassland ecosystem services under climate change

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ABSTRACT

Ecosystem and associated services in arid and semiarid areas are sensitive to climate change and human activities. Guiding human activities based on the optimization of ecosystem services can help humans adapt to climate change effectively, which is vital for regional sustainability. We evaluated the distribution of five ecosystem services: net primary productivity (NPP), soil conservation (SC), water yield (WY), water retention (WR), and livestock supply in the grassland and agro-pastoral transitional zone of China (GAPTZ) under the future climate scenarios of representative concentration pathway (RCP) 4.5 and RCP8.5 in 2050. We designed the four grazing-intensity scenarios of ungrazed (UG), lightly grazed (LG), moderately grazed (MG), and heavily grazed (HG) and analyzed the impacts of climate change and grazing on the ecosystem services. Finally, we presented the optimization schemes of grazing intensity in the GAPTZ under the objectives of "strong sustainability" and "weak sustainability". "Strong sustainability" objective means that the total change rate of ecosystem services compared to the ungrazed scenario is maximal and should not be less than 0. "Weak sustainability" objective means that the livestock supply is preferential and the total change rate of ecosystem services compared to the ungrazed scenario is maximal but could be less than 0. The results showed that both climate change and grazing exert great influence on the supply and interrelation of ecosystem services. In the northeast of the GAPTZ, LG and MG can stimulate grassland to tiller and enlarge ecosystem services integrally. HG has the severest negative effect on ecosystem services overall. Under the "weak sustainability" objective, LG can be widely adopted in the GAPTZ. Under the "strong sustainability" objective, grazing should be limited in the northwestern and north-central GAPTZ. Reasonable planning of grazing intensity and its spatial patterns can promote effective utilization of grassland resource and realization of regional sustainability.

1. Introduction

Climate change and human improper utilization of natural resources can both possibly result in degradation of ecosystems (Stocker, 2013). Ecosystem services, the benefits that humans obtain from natural ecosystems, are critical for human wellbeing and regional sustainability (Wu, 2013). Under the pressures of climate change and human activities, such as overgrazing, intensive agricultural production, deforestation, and urbanization, the supply of multiple ecosystem services worldwide significantly decreases (Costanza et al., 2014). On one hand, climate is the direct driving force for many ecosystem services (Piao et al., 2006). On the other hand, it could indirectly affect ecosystem service supply by changing the structure and spatial pattern of the ecosystems (Guerra et al., 2016). Human activity usually affects the biophysical parameters of surface, in turn affecting the supply of ecosystem services (Hao et al., 2017; Fezzi et al., 2015). There exists complex interrelation among ecosystem services. When some services are given perference by humans, other services might be affected (Bennett et al., 2009). Therefore, overall optimization of regional key ecosystem services under future climate change bears important practical significance for achiveing regional sustainability.

To date, many studies have been conducted on ecosystem service management from the aspect of adaption to climate change. For example, Albert et al. (2015) used ecosystem services as indicators of landscape planning and compared their possible change between the current and the future. How to create a win–win situation among all

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stakeholders is a key task for landscape planning (Howe et al., 2014). In the existing studies of optimization on multiple ecosystem services, researches usually set the change of land-use/cover type as the scenario variable (e.g., Claessens et al., 2009; Fezzi et al., 2015; Langemeyer et al., 2016). With regard to a region where land-use/cover type, like grassland, is relatively unchanged, few studies set the changes in biophysical parameters, like vegetation cover fraction to represent the intensity of human activities (e.g. Nelson et al., 2009).

The grassland and agro-pastoral transitional zone of China (GAPTZ) is one of the largest ecotones in the world. It is an important ecological shelter for agricultural plains in Eastern China and for cities in Northern China (Gao et al., 2000). GAPTZ can provide multiple ecosystem services such as agricultural products, recreation, water purification, runoff regulation, and climatic regulation, etc. However, drying and warming trend of climate change and overgrazing have resulted in serious desertification with an areas of 0.39 million km^2 until now (Wang et al., 2004). Some ecosystem services, such as primary productivity, soil conservation, and climatic regulation, have been significantly affected (Xiao et al., 1995; Bai et al., 2004; Zhang et al., 2011; Hao et al., 2017).Qiu et al. (2016) found that soil carbon storage of the grassland in Northern China would significantly decrease in the future climate scenario.

The main objectives of this study are to identify the role of grazing activity in impacting ecosystem services under the future climate scenarios and look for effective adaptive measures to the future climate change. The research questions in this study are: 1) how to analyze the impact of grazing intensity on ecosystem services based on the spatial distribution patterns of the ecosystem services in the GAPTZ under the future climate scenarios? and 2) how to make the optimal schemes of grazing intensity based on different sustainability objectives under the climate scenarios?

2. Materials and methods

2.1. Study area

The GAPTZ is located between 34°58′–50°19′N latitude and 101°–124°75′ E longitude. The GAPTZ undergoes a typical temperate semiarid and arid continental monsoon climate with heavy wind and low precipitation. Precipitation is concentrated in summer (July to September). A high plain is the main topographic feature and sandy and loamy soils are the main soil types. Approximately 60% of the area in the GAPTZ is grassland (Fig. 1). There are 47 animal husbandry banners and the GAPTZ ranks the first in holding quantity of livestock species, such as cattle, horse, and sheep (Inner Mongolia Statistical Yearbook, 2014).

2.2. Vegetation types and the future climate scenarios

The vegetation type is the result of interaction of many factors, such as topography, soil, and climate. We assumed that the spatial distribution of the main natural vegetation types in the GAPTZ in 2050 would be the same as that in the current period (Fig. 1). The spatial distribution of vegetation types in the GAPTZ was provided by the Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (RESDC) (http://www.resdc.cn). The dataset presents the distribution of 11 vegetation type groups, 796 vegetation units of formation and 54 vegetation sub-formation, and the distribution of more than 2000 dominant species of plant, staple crops, and industrial crops. The dataset was finished over 30 years from 1980s to 2008. In the GAPTZ, the dominant species of steppe mainly includes *Leymus chinensis*, *Stipa bungeana*, and *Stipa grandis* in the dataset. The dominant species of meadow includes *Achnatherum splendens* and *Artemisia lancea Van*. The dominant species of desert vegetation includes *Caragana Korshinskii Kom.*, *Artemisia sphaerocephala Krasch.*, and *Reaumuria soongorica*. The dominant species of shrub includes *Hippophae rhamnoides Linn.*, *Vitex negundo* L., and *Caragana microphylla Lam.*

Future climate data are from the dataset of the daily weather report in East Asia of 2050. The Coordinated Regional Climate Downscaling Experiment (CORDEX) produced this dataset using the HadGEM3-RA Model. The data resolution of CORDEX is 0.44° × 0.44°, including climate factors of daily precipitation, solar radiation, wind speed, daily maximum temperature, daily minimum temperature, and relative humidity (Table 1). This study chose two future climate scenarios of RCP4.5 and RCP 8.5. RCP 8.5 represents a high-end pathway that falls in the 90th percentile in the CO_2 emission range and its radiative forcing level is the highest among the RCPs. RCP4.5 is a medium and stable pathway and it is in line with the measures of economic development and adaption to climate change in China (Gao et al., 2014).

2.3. Evaluation of ecosystem services

As a supporting service, NPP is the basis for sustaining grassland productivity and other ecosystem services. In the GAPTZ, the most important limiting factor for vegetation growth is water supply (Hao et al., 2017), so the regulating services of water yield (WY) and water retention (WR) are important. With precipitation concentrating in the summer and mutative slope in the GAPTZ, soil erosion is easily triggered (Hao et al., 2017). The aim of soil conservation (SC) is to protect land and reduce loss of soil erosion. Livestock supply is one of the most important provisioning services in the GAPTZ (Inner Mongolia Statistical Yearbook, 2014). Therefore, we considered NPP, SC, WY, WR, and livestock in this study.

We used the Denitrification-Decomposition model (DNDC) (Li et al., 1992) to estimate NPP under the future scenarios. DNDC is a mechanism model based on ecological process of the interaction among climate, soil, terrain, vegetation, and human management. By inputting daily weather data, soil parameters, crop parameters of biomass fraction of grain, leaf, steam and root, and human management measures of irrigation, grazing and cutting, DNDC calculates plant growth per day according to daily temperature and water conditions and distributes the growth amount to the root, stem, leaf, and grain (Li et al., 1997; Zhang et al., 2002). In this study, we input the future daily climate data of the GAPTZ under the climate scenarios of RCP4.5 and RCP8.5 in 2050 (Table 1) into the DNDC model to simulate NPP at the pixel level. Thus, we could obtain the spatial distribution of NPP in the future. By comparing the needed daily fodder amount for the livestock per hectare and the daily plant biomass of the grassland, grazing intensity of NPP was calculated (Li, 2016).

To ensure the accuracy of simulating NPP through DNDC, this study formulated the parameters combining the built-in physiological parameter of perennial grassland in DNDC and the physiological parameter of plant in relevant literatures in the GAPTZ (Cui et al., 2015; Guo et al., 2011; Jin et al., 2012; Li, 2015; Ren et al., 2009; Yang et al., 2013). We validated the result of NPP simulated by DNDC withthe field measured NPP (Fig. 2). The field measured data of NPP includes 76 sample points covering multipe grassland types and scattering in the GAPTZ (Table 2). The year of climate data used to validate the simulation accuracy of DNDC model is the same as the year of field measured NPP (Table 1). After the validation, the root mean square error (RMSE) beween the field measured NPP and the result of DNDC simulation is 13%. The result of linear regression of the two (Fig. 2) also indicates that DNDC is robust to estimate NPP in the GAPTZ accurately.

The Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1991) was used to calculate SC as the Eq. (1).

$$SC = R \times K \times LS - R \times K \times LS \times C \times P \quad (1)$$

SC is the amount of annual soil conservation ($ton \cdot ha^{-1} \cdot y^{-1}$). R is the precipitation erosivity factor ($MJ \cdot mm \cdot ha^{-2} \cdot ha^{-1} \cdot y^{-1}$) (Wischmeier and Smith, 1965), which is calculated based on daily rainfall. K is the soil erodibility factor, calculated based on soil data ($ton \cdot h \cdot MJ^{-1} \cdot mm^{-1}$)

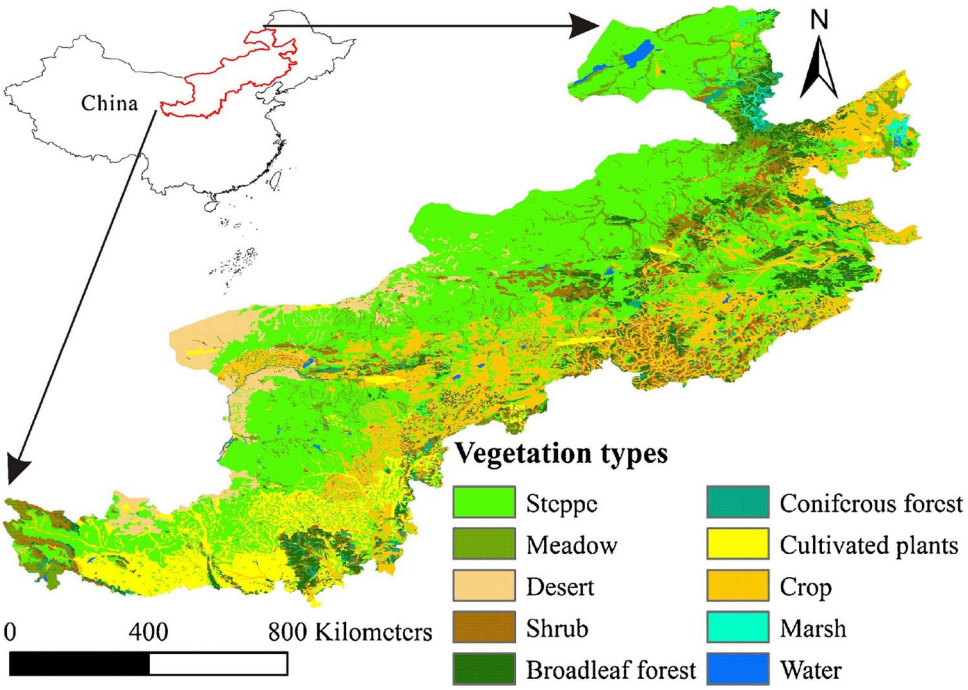

Fig. 1. Location and spatial distribution of vegetation types in the current period of the grassland and agro-pastoral transitional zone of China (GAPTZ).

Table 1
Data used in this study and their sources.

Data type	Data description (unit)	Data source
Future climate data of RCPs	Daily relative humidity (%) Daily maximum temperature (°C) Daily minimum temperature (°C) Daily rainfall (mm) Daily mean wind speed (m/s) Daily solar radiation (W/m^2)	Coordinated Regional Climate Downscaling Experiment (CORDEX) (http://www.cordex.org)
Climate data for NPP validation	Daily relative humidity (%) Daily maximum temperature (°C) Daily minimum temperature (°C) Daily rainfall (mm) Daily mean wind speed (m/s) Daily solar radiation (W/m^2)	China Meteorological Sharing Service System(http://data.cma.cn/)
DEM	Digital Elevation Model (m)	Geospatial Data Cloud, Computer Network Information Center, Chinese Academy of Sciences
Soil data	Soil texture, topsoil clay fraction (%), topsoil organic carbon (kg/C), soil PH, and bulk density(g/cm^3)	Cold and Arid Regions Science Data Center at Lanzhou
Vegetation types	Spatial distribution of vegetation in China with the scale of 1:1000000	Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (RESDC) (http://www.resdc.cn)
Parameters of grass and crop	Max biomass production(kg C/ha) Biomass fraction of grain, leaf, stem, and root Biomass C/N ratio of grain, leaf, stem, and root Annual N demand(kg N/ha) Thermal degree days for maturity Water demand (g/ha) Optimum temperature (°C)	Literature search and adjusting parameters by model validation (see Table A1)
Observed NPP	NPP obtained through field measurements (kg C/ha)	Literature search (details in Table 2)
NDVI and LAI	Monthly Normalized Difference Vegetation Index (NDVI) and Leaf Area Index (LAI) from 2000 to 2015	Geospatial Data Cloud, Computer Network Information Center, Chinese Academy of Sciences

(Wischmeier and Smith, 1978). LS is the factors of slope length and steepness (Mccool et al., 1987), which are calculated based on the Digital Elevation Model (DEM) using ArcGIS9.3 (Esri, US). P is the factor of land management using Werner's slope-based method (Jia et al., 2014). C is the vegetation coverage factor. To calculate the C factor in the future scenarios, we first calculated the averages of the Normalized Difference Vegetation Index (NDVI) and the Leaf Area Index (LAI) in every pixel under the resolution of 0.44° × 0.44° during the period from 2001 to 2015 in the GAPTZ. Second, we obtained the regression relationship between the NDVI and the LAI (Fig. 3). Then, we used the LAI simulated by the DNDC (Zhang et al., 2002) to calculate the NDVI in the future climate scenarios based on the relationship. Finally, we got the C factor by using the algorithm in the study of Cai et al. (2000).

Both WY and WR were evaluated using the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) Model (Sharp et al., 2015). WY is the same as surface runoff. In the InVEST model, WY is calculated based on the principle of water balance and represents reservoir hydropower production. In Eq. (2), WY is annual water yield (mm). P is

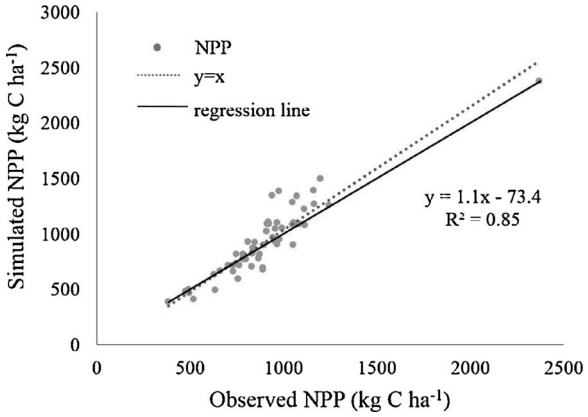

Fig. 2. Validation of simulated NPP by DNDC.

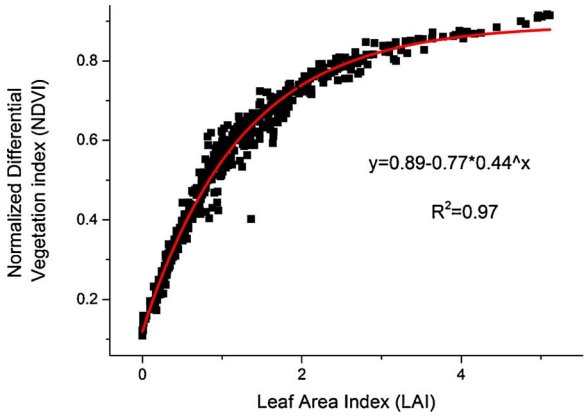

Fig. 3. Regression between the NDVI and the LAI in the GAPTZ.

annual precipitation (mm). AET is actual evapotranspiration (mm), which is calculated based on the algorithm in Sharp et al. (2015). WR is the part of WY retained by soil. The terrain and land cover affect the WR amount by changing the runoff velocity. In Eq. (3), WR is water retention (mm). TI is the topographic index, calculated based on DEM (Sharp et al., 2015). Ksat is soil saturated conductivity (cm/d) calculated using Neuro Theta software (University of Sydney, Australia). V is surface velocity coefficient (Sharp et al., 2015).

$$WY = P - AET \quad (2)$$

$$WR = Min(1,0.9 \times TI/3) \times Min(1, Ksat/300) \times Min(1,249/V) \times WY \quad (3)$$

2.4. Setting the grazing-intensity scenarios

When the utilization ratio of aboveground biomass of the grassland in Northern China is about 50% of pasture productivity, the grazing intensity should be appropriate for the balance between forage supply and animal need without resulting in serious degradation of grassland (Li, 2003; Lin et al., 2008; Yang et al., 2001). In this study, we set moderately grazed (MG) for the utilization ratio of the average NPP at 50% of the ungrazed (UG) scenario. Besides, we designed lightly grazed (LG) and heavily grazed (HG) for the utilization ratio of the average NPP at 25% and 75% respectively. We calculated the average NPP of each vegetation type (Fig. 1) under the UG scenario firstly. According to the utilization ratios of the average NPP in different grazing scenarios, we obtained the NPP consumption amount for each grid for each grassland type under the LG, MG, and HG scenarios. The DNDC model sets that the NPP consumption amount of one sheep in a free-grazing condition for one year is 183 kgC (Li, 2016), on which we based our calculation of livestock supply for each hectare under the grazing intensities of LG, MG, and HG for different grassland types (Table 3). We input the livestock supply into the DNDC model to calculate the corresponding NPP under different grazing intensities. This study assumed that animal excrement is left in the ground when driving DNDC.

Table 3
Livestock density under LG, MG, and HG for different grassland types.

Vegetation	LG (Sheep/ha)		MG (Sheep/ha)		HG (Sheep/ha)	
	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5
Meadow	3	2.8	6.1	5.7	9.1	8.5
Steppe	2.1	2.3	4.3	4.7	6.4	7
Desert	0.44	0.5	0.87	1	1.31	1.5
Shrub	3.1	3.3	6.2	6.5	9.3	9.8
Cultivated plants	2.3	2.3	4.5	4.5	7	7

In order to clearly characterize the variation of ecosystem services with grazing intensity, we calculated the change rate of each ecosystem service compared with the UG scenario (Eq. (4)). Spearman's correlation analysis at the pixel level was used to characterize the relationship between ecosystem services under the different grazing intensity scenarios, with significant positive correlation indicating synergy and the converse indicating tradeoff. Because livestock supply presented the grazing intensity, we did not analyzed its change rate and correlation with other ecosystem services.

$$C_ES_i = (ES_i - ES_{UG})/ES_{UG} \quad (4)$$

In Eq. (4), C_ES stands for the change rate of certain ecosystem services (NPP, SC, WY, WR) compared with the UG scenario and i stands for grazing intensity (i = HG, MG, LG).

Table 2
The samples of field-measured NPP.

Sample name	Longitude	Latitude	Time	Number of samples	Vegetation name	Source
Tumugi	123	46.1	1981–1990	10	*Leymus chinensis*	OAK RIDGE National Laboratory
Xilingol	116.6	43.7	1980–1989	10	*Leymus chinensis*	OAK RIDGE National Laboratory
Dalai Nur	115.7	43.4	2005	1	*Stipa grandis*	(Gao, 2005)
Songnen	123.8	44.6	1991	1	*Leymus chinensis*	(Wang et al., 2002)
Ewenki Banner	119.8	48.9	1984–1995	12	*Leymus chinensis*	(Bai et al., 2001)
Ewenki Banner	119.7	48.5	2004	1	*Leymus chinensis*	(Yang et al., 2006)
Xiwuqi	117.6	44.5	1984–1995	12	*Stipa grandis*	(Bai et al., 2001)
Zhenglanqi	116.1	42.3	1984–1995	12	*Leymus chinensis*	(Bai et al., 2001)
Damaoqi	110.6	42.1	1984–1995	12	*Reaumuria soongorica*	(Bai et al., 2001)
Siziwang Banner	111.9	41.8	2002	1	*Stipa krylovii Roshev*	(Bili et al., 2004)
Zhengxiangbai Banner	115.26	42.15	2009	3	*Leymus chinensis*	(Bili et al., 2004)
Xilingol	116.33	43.13	2005	1	*Leymus chinensis*	(Geng, 2006)

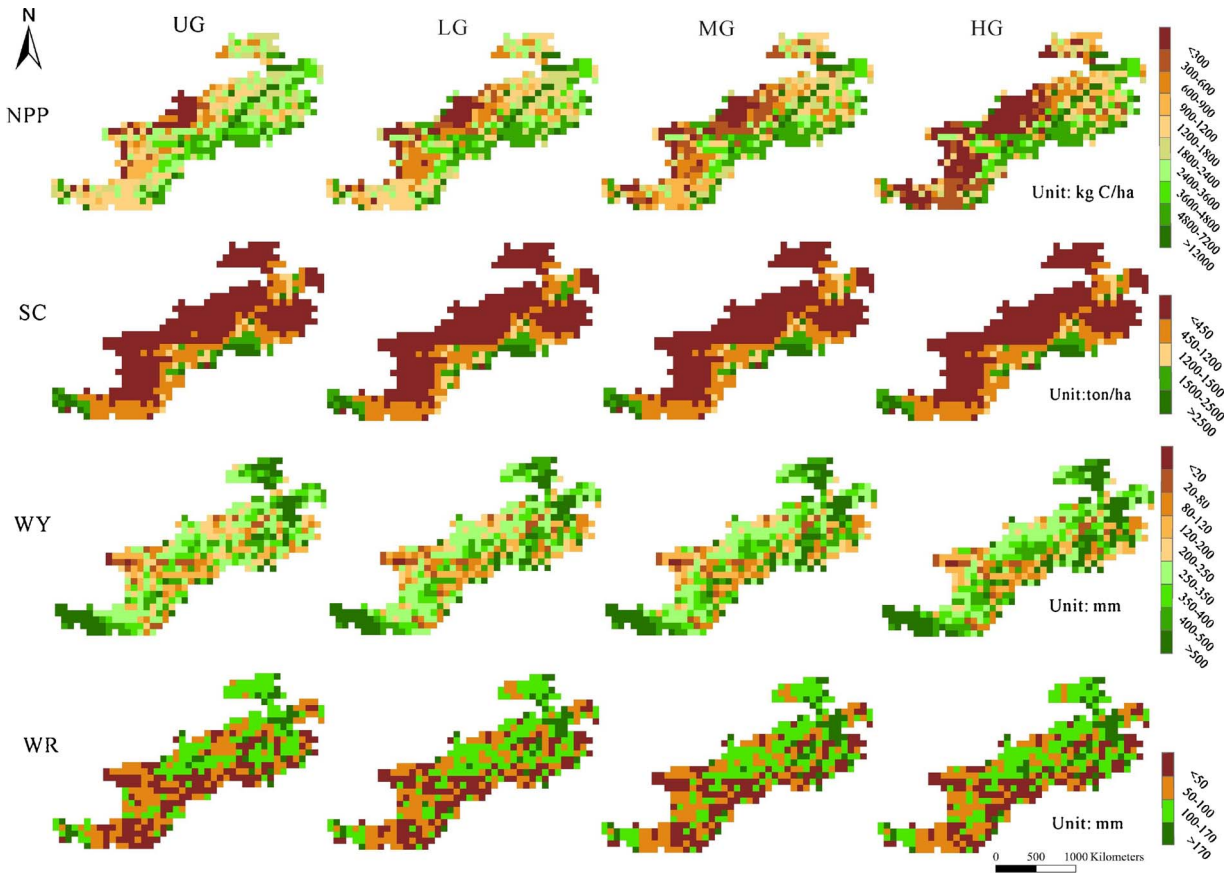

Fig. 4. The spatial distributions of ecosystem services in the RCP4.5 scenario under different grazing intensity scenarios. NPP, SC, WY, and WR stand for net primary productivity, soil conservation, water yield, and water retention, respectively; UG, LG, MG, and HG represent the grazing scenarios of ungrazed, lightly grazed, moderately grazed, and heavily grazed, respectively.

2.5. Optimization of ecosystem services

We set two objectives called “strong sustainability” and “weak sustainability” for future development based on Wu (2013)’s definition. Sustainability contains three dimensions: environmental conservation, economic development, and social fairness with the aim of achieving a balance between human demands and environmental integrity (Wu, 2013). “Strong sustainability” assumes the environmental dimension constrains the other two dimensions while “weak sustainability” allows mutual substitutability of the three dimensions as long as the total capital does not decrease (Wu, 2013).

In the study, livestock density is calculated by the NPP consumption amount and it is the economic dimension of sustainability. Therefore, we made the livestock density as the role of priority for the optimization of ecosystem services. “Weak sustainability” in this study means to set an appropriate supply of livestock as the premise and to achieve overall optimization of ecosystem services without considering the decrease in ecosystem services resulting from grazing activity compared with the UG scenario. To take full advantage of the different tolerances of grazing intensity in space, we calculated the optimal grazing intensity at the pixel level. The calculation algorithms of optimal grazing intensity are indicated as the following Eq. (5–7).

At the grid level:

$$sum_i = C_NPP_i + C_SC_i + C_WY_i + C_WR_i \quad (5)$$

$$M = \max(sum_{HG}, sum_{MG}, sum_{LG}) \quad (6)$$

$$SG = \begin{cases} HG\,(if M = sum_{HG}) \\ MG\,(if M = sum_{MG}) \\ LG\,(if M = sum_{LG}) \end{cases} \quad (7)$$

In Eq. (5), i stands for grazing intensity (i = HG, MG, LG); C_ecosystem service stands for the change rate of certain ecosystem services (NPP, SC, WY, WR); M is the maximum sum of change rates of ecosystem services under different grazing intensities. A positive value means the ecosystem services are larger than the UG scenario, and a negative value indicates the converse. SG is the judgment function to suggest the optimal grazing intensity at the pixel level.

Strong sustainability in this study means that if the total ecosystem services under any grazing intensity in LG, MG, or HG is lower than under ungrazed conditions, then grazing should be limited.

4. Results

4.1. Ecosystem services in the future scenarios

Generally, the spatial patterns of the four ecosystem services of NPP, SC, WY, and WR under the different scenarios are similar (Figs. 4 and 5,). Low NPP values (< 200 kg C/ha) distribute in the north-central and northwest GAPTZ. Under the different scenarios, the spatial distributions of SC are generally similar: the high value appears in the northeast-central band extending to the south margin of GAPTZ (Figs. 4 and 5). The spatial distributions of WY vary slightly with grazing intensity, and the difference is mainly reflected in the south-central (RCP4.5) and central (RCP8.5) GAPTZ. From UG to LG, WR in the central part of GAPTZ is obviously increased (Figs. 4 and 5).

In the future scenarios, meadows and steppes will be the main regions to supply livestock, and the supply amount would account for almost 70% of the livestock amount in the GAPTZ (Table 4). Under the HG scenario, the livestock supply amount is more than that under the LG and MG scenarios (Table 4).

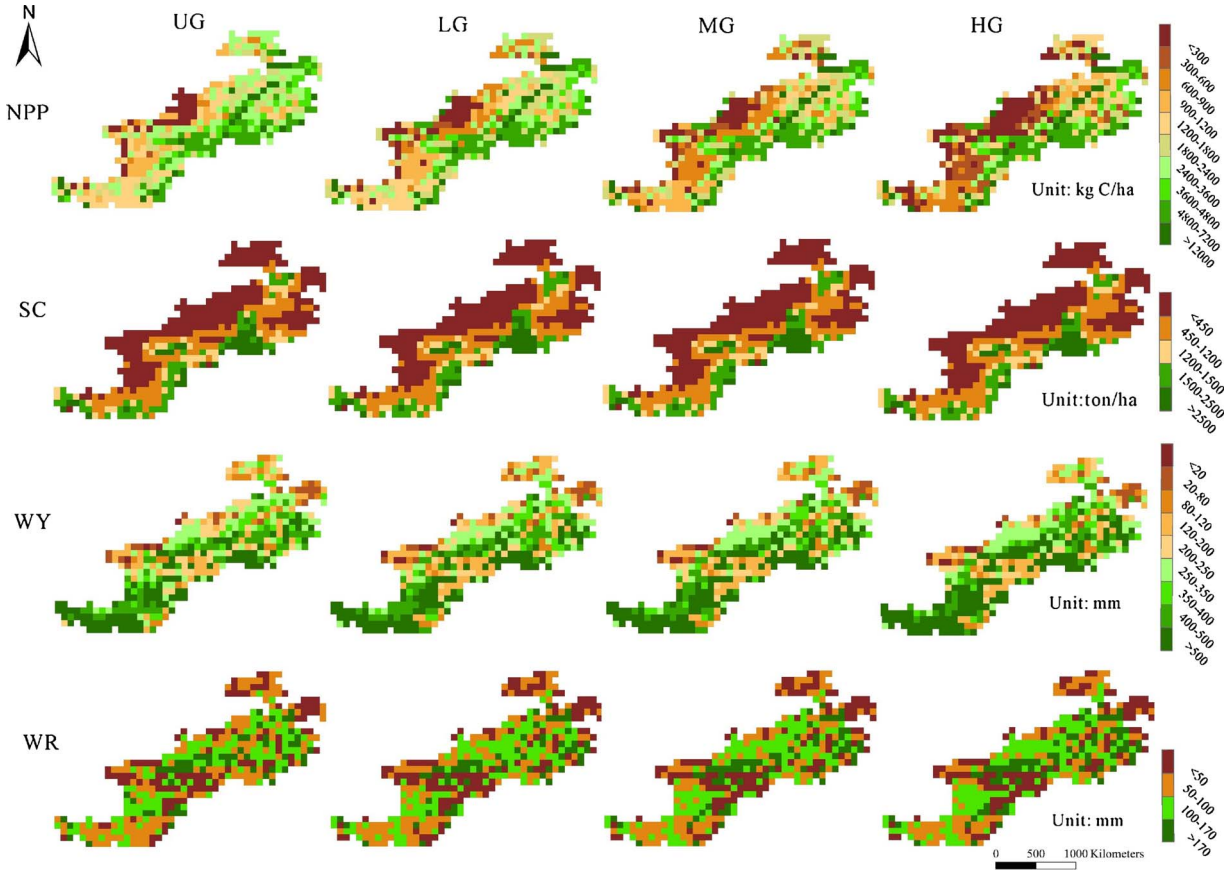

Fig. 5. The spatial distributions of ecosystem services in the RCP 8.5 scenario under the different grazing intensity scenarios.

Table 4
Livestock supply service in the future scenarios.

Vegetation types	RCP4.5(unit: Million sheep)			RCP8.5(unit: Million sheep)		
	LG	MG	HG	LG	MG	HG
Meadow	6.8	13.7	20.5	6.36	12.8	19.2
Steppe	8.0	15.8	23.8	8.7	17.4	26
Desert	0.65	1.3	1.9	0.74	1.5	2.2
Shrub	3.2	6.5	9.8	3.46	3.46	10.3
Cultivated plants	2.9	5.6	8.7	2.8	5.6	8.68
Sum	21.55	42.9	64.7	22.06	44.76	66.38

4.2. Variation of ecosystem services under the different climate and grazing scenarios

The change trends of ecosystem services under the RCP4.5 scenario are similar to those under the RCP8.5 scenario with increasing grazing intensity (Fig. 6). From LG to HG, the averages of NPP and SC decrease, while the averages of WY, and WR increase (Fig. 6). Generally, the values of NPP, SC, WY, and WR under the RCP8.5 scenario are greater than those under the RCP4.5 scenario. For example, the average SC under the RCP8.5 scenario is almost two times as high as the average SC under the RCP4.5 scenario (Fig. 6).

Generally, the spatial distribution patterns of change rate of ecosystem services under the climate scenarios of RCP4.5 and RCP8.5 are similar (Figs. 7 and 8,). Under the different grazing scenarios, the change rates of NPP, SC, WY, and WR are almost distributed in the range of −1 to 1 (Table A2 and Table A3). HG could significantly impact on the four ecosystem services (Figs. 7 and 8 and Table A2-Table A3). The north-central and west part of GAPTZ are the sensitive areas where ecosystem services are affected greatly by grazing.

Under the different grazing scenarios, the change rates of NPP are all negative (Fig. 7 and Fig. 8). With grazing intensity increased, the area where the change rate of NPP falls in the range from −100% to−50% increases quickly, under HG scenario, which covers 42% (RCP4.5) and 36% (RCP8.5) of the GAPTZ respectively (Table A2 and Table A3). Compared with the other two grazing scenarios, the impact of HG on SC is more greatly. The area with the change rate of SC falling in −50% to 0 covers about 52% (RCP4.5) and 50% (RCP8.5) of the GAPTZ respectively (Table A2 and Table A3), which almost covers the entire grassland (Figs. 1, 7 and 8). The area where the change rates of WY within the ranges of −50%-0 and 0–50% are significantly affected by increasing grazing intensity, with the coverage percentage decreasing from 31% to 11% and increasing from 31% to 49% respectively (Table A2 and Table A3). Under the different grazing intensity, the spatial distribution patterns of the change rate of WR resembles that of WY (Figs. 7 and 8).

4.3. The interrelation between ecosystem services in future climate and grazing scenarios

Under the RCP4.5 scenario, the interrelations between ecosystem services in different grazing intensities are similar, while they are slightly different under the RCP8.5 scenario, especially for SC and WR. SC is insignificantly negatively correlated ($P > 0.01$) with WR under the RCP4.5 scenario, while it is significant positively correlated ($p \leq 0.01$) in the scenarios of UG and LG and insignificant positively correlated ($P > 0.01$) in the scenarios of MG and HG under the RCP8.5 scenario (Table 5).

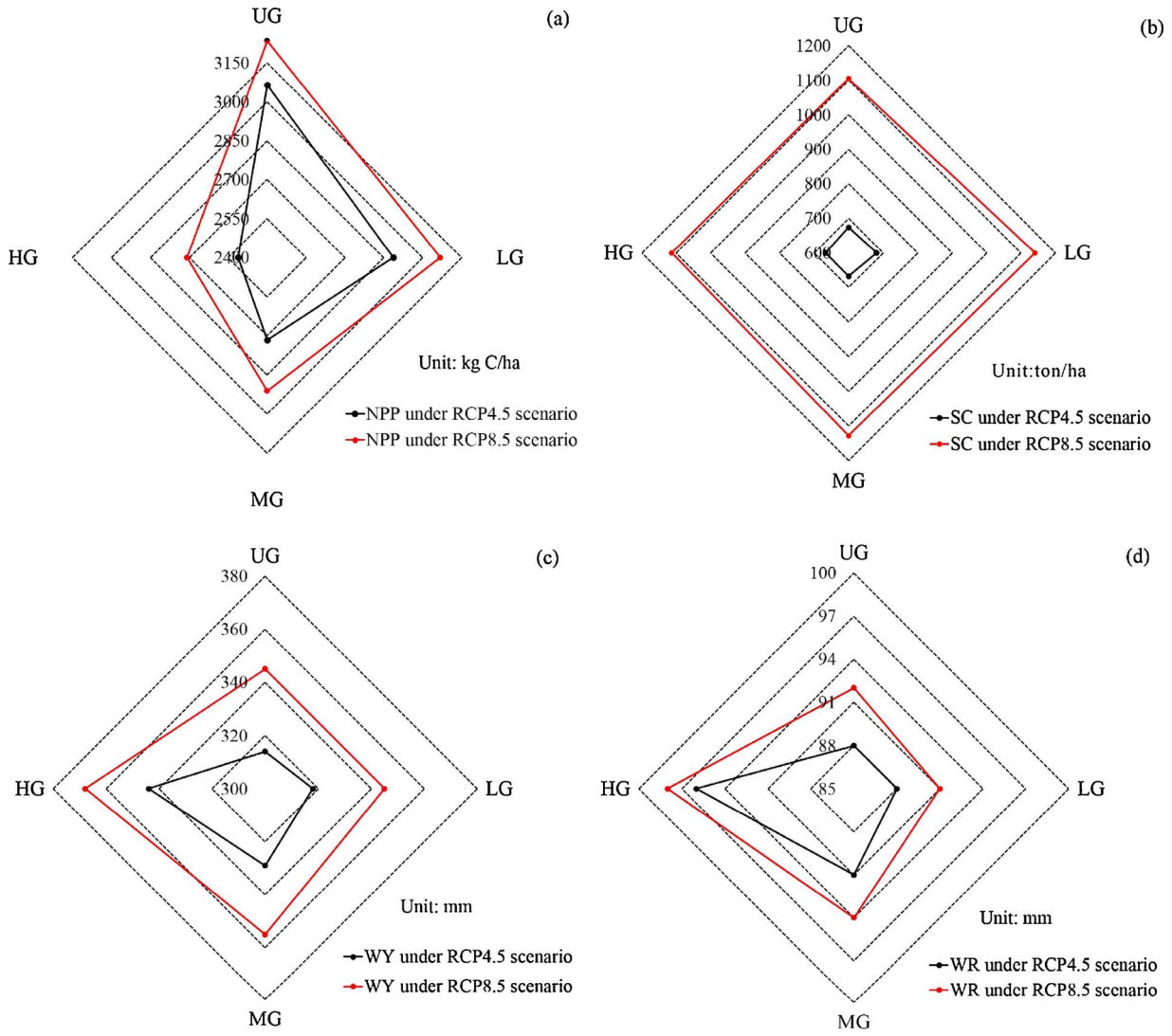

Fig. 6. Variation of ecosystem services with the climate and grazing scenarios. a, b, c, d are the averages of NPP, SC, WY, and WR under different scenarios, respectively.

4.4. Optimization of ecosystem services under the sustainability objectives

Under the "weak sustainability" objective, LG covers the largest area and the appropriate areas for MG are generally gathered in the west and central parts. The appropriate areas for HG are small and generally distributed in the alfalfa planting (*Medicago sativa* L.) in arid regions (Fig. 9(a) and Fig. 9(b)). Under the "weak sustainability" objective, a high value of livestock supply appears in the northeast GAPTZ under both climate scenarios of RCP4.5 and RCP8.5 (Fig. 9(c) and Fig. 9(d)). The livestock supply amount is 23.5 million sheep (RCP4.5) and 22.8 million sheep (RCP8.5) at the optimal grazing intensity (Table 6).

Under the "strong sustainability" objective, most areas in the north-central and west GAPTZ should limit grazing activity (Fig. 10(a) and Fig. 10(b)). In the central GAPTZ, the difference of grazing intensities under the RCP 4.5 and the RCP8.5 scenarios is distinct (Fig. 10(c) and Fig. 10(d)). With the optimal grazing intensity, the livestock supply amount is 8 million sheep (RCP4.5) and 8.3 million sheep (RCP8.5) (Table 6). This livestock supply is considerably less than under the "weak sustainability" objective but the whole ecosystem services are much more superior (Table 6).

5. Discussion

5.1. Potential driving forces of ecosystem service variation in the future scenarios

Generally, precipitation has positive effect on NPP, SC, WY,and WR in the semiarid region, like our study areas where moisture is a critical factor restricting vegetation growth as well as related ecosystem services (Hao et al., 2017). In the GAPTZ, the annual mean precipitation in the RCP4.5 scenario (577 mm) is less than that in the RCP8.5 scenario (622 mm), so that the averages of NPP, SC, WY, and WR are much higher in the RCP8.5 scenario. Except for climate change, grazing activities as well as other factors, such as soil type and terrain (Hao et al., 2017), will exert a joint great influence on the supply and interrelation of ecosystem services. In this study, due to the combined effects of precipitation patterns and topography, the areas with high SC value are mainly distributed in the central and southern regions and along the western margins of the GAPTZ.

Grazing activity could directly affect NPP and SC by changing the vegetation coverage and indirectly impact WY by changing plant transpiration (Chen and Zou, 1998; Jia et al., 2014; Hao et al., 2017). In the northwest and north-central GAPTZ, where the main vegetation is of the desert type with a low grazing tolerance, the ecosystem services of NPP, SC, WY, and WR are sensitive to grazing interruption, even

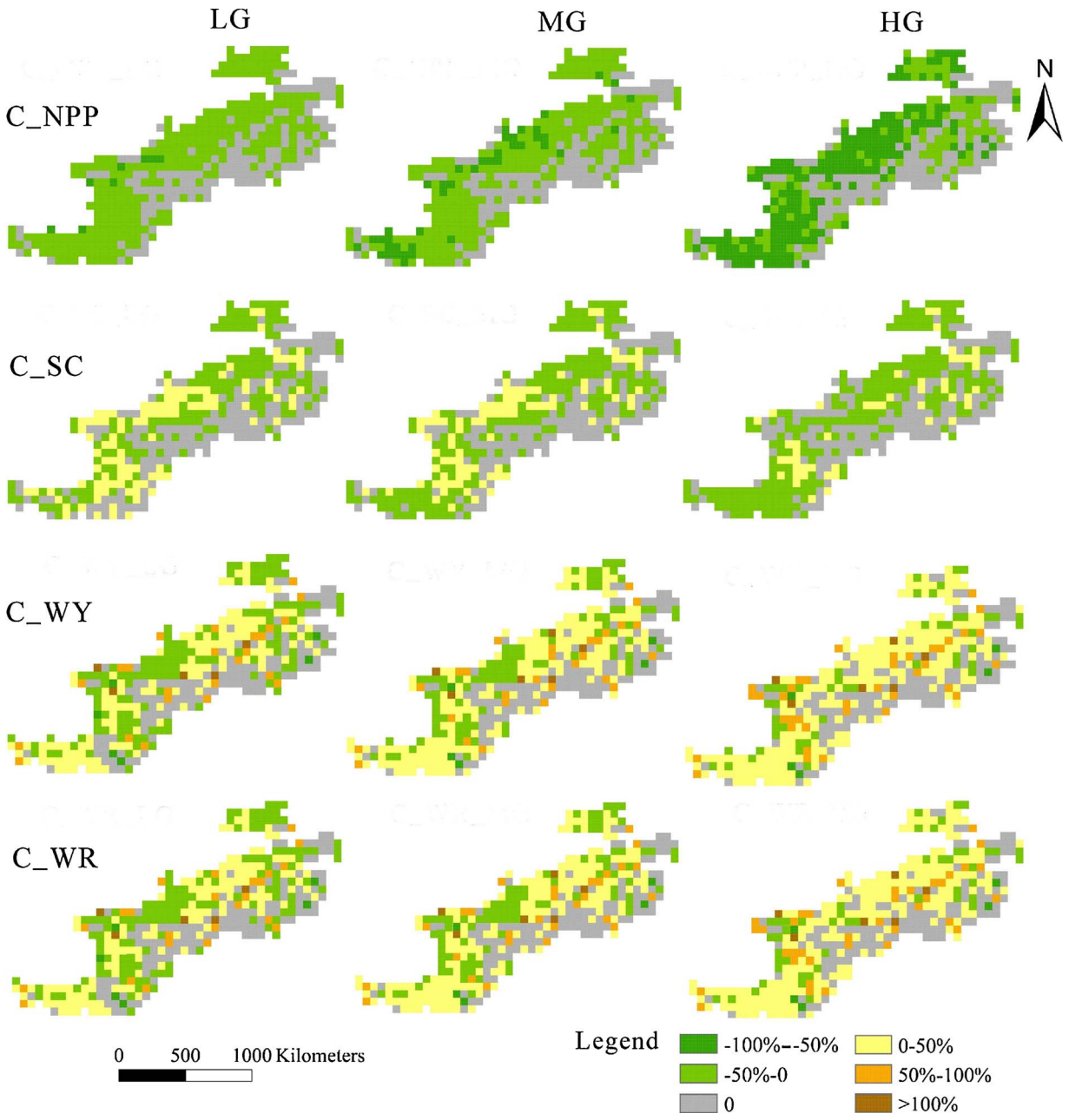

Fig. 7. The change rate of each ecosystem service compared with that in UG scenario in the climate scenario of RCP 4.5 under different grazing intensity scenarios.

lightly grazing intensity (Figs. 9 and 10). HG could obviously decrease NPP and SC with eating off the reproductive branch (Cheng and Zou, 1998). However, HG would increase WY and WR significantly (Fig. 8). The main reasons may be that HG decreases vegetation evapotranspiration and leads to more surface water. Additionally, HG would result in an increase in soil compaction with more livestock treading on the soil and then reducing the amount of infiltration (Wang et al., 2005). Therefore, in the GAPTZ, the regional hydrological cycle would be significantly affected by grazing intensity. A significant decrease in water utilization by plants and an increase in water availability for human industrial production and living are shown, while the risk of regional water loss and soil erosion, floods and other natural disasters may greatly increase accordingly.

5.2. Implications for regional grassland management

In this study, under the "strong sustainability" objective, the total grassland ecosystem services of the UG scenario is the natural capital that constrains the grazing activity; under the "weak sustainability" objective, the livestock supply substitutes for NPP. The GAPTZ is one of the important areas of livestock supply in China, and animal husbandry is the main economic source for local herdsmen (Inner Mongolia Statistical Yearbook, 2014). Only considering the economic interest of herdsmen, HG is the preferential choice under the different climate scenarios, as Table 4 shows. However, HG is not a sustainable strategy with negative effect on ecosystem services. Chen and Zou (1998) and Bili et al. (2004) also found the similar results.

Either under the "weak sustainability" objective or "strong sustainability" objective, meadows and steppes will mainly carry livestock supply and raise approximately 70% livestock of the GAPTZ (Table 4, Figs. 9 and 10). It is important to appropriately use the biomass in meadows and steppes. LG under "weak sustainability" objective and UG under "strong sustainability" objective may be chosen in the meadows and steppes in GAPTZ (Figs. 9 and 10). With increasing human

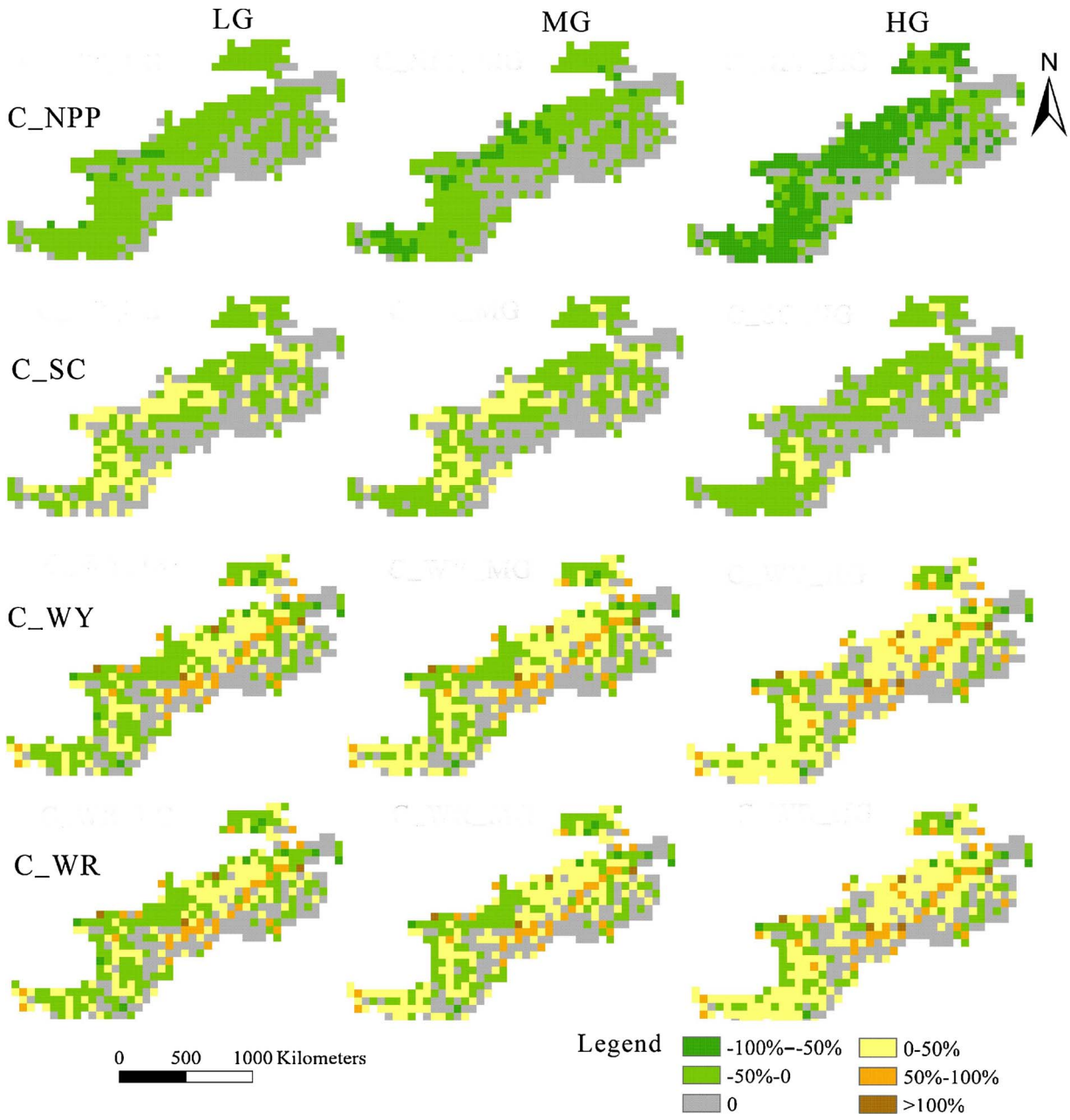

Fig. 8. The change rate of every ecosystem service compared with that in UG scenario in the climate scenario of RCP 8.5 under different grazing intensity scenarios.

Table 5
Spearman's correlation coefficients of paired ecosystem services under the different scenarios and *p*-values in the bracket.

		NPP_SC	NPP_WY	NPP_WR	SC_WY	SC_WR	WY_WR
UG	RCP4.5	0.49(0)	−0.30(0)	−0.33(0)	0.12(0.01)	−0.08(0.11)	0.77(0)
	RCP8.5	0.44(0)	−0.33(0)	−0.39(0)	0.34(0)	0.13(0.01)	0.74(0)
LG	RCP4.5	0.49(0)	−0.30(0)	−0.35(0)	0.17(0)	−0.05(0.26)	0.77(0)
	RCP8.5	0.46(0)	−0.30(0)	−0.36(0)	0.33(0)	0.14(0)	0.75(0)
MG	RCP4.5	0.48(0)	−0.29(0)	−0.33(0)	0.16(0)	−0.07(0.15)	0.77(0)
	RCP8.5	0.47(0)	−0.30(0)	−0.36(0)	0.31(0)	0.12(0.01)	0.75(0)
HG	RCP4.5	0.44(0)	−0.32(0)	−0.33(0)	0.14(0)	−0.09(0.07)	0.76(0)
	RCP8.5	0.45(0)	−0.36(0)	−0.32(0)	0.30(0)	0.10(0.04)	0.75(0)

demands for meat in the future (Pradhan et al., 2013a) and crop calories being used as livestock feed, grassland plays an increasing critical role in providing missing human nutrition (Pradhan et al., 2013b). Therefore, it is important to balance the development objectives of "strong sustainability" and "weak sustainability" in grassland according to the situations of natural conditions and human demands. At the large scale, "strong sustainability" is necessary to ensure lasting and stable service provision by the natural ecosystems, while in the areas with superior natural conditions and enduring larger intensity of grazing to some extent, "weak sustainability" can be accepted to make full use of

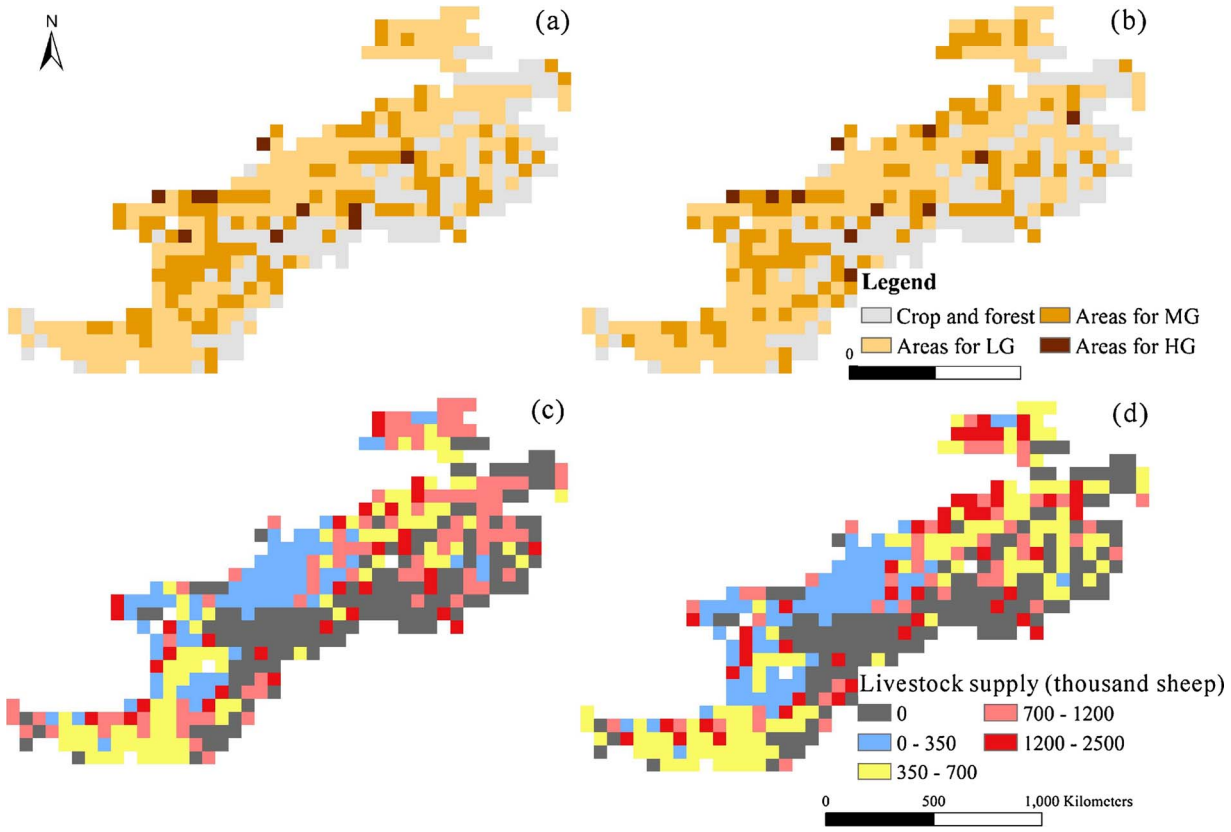

Fig. 9. (a) and (b) present the optimal grazing intensity based on the objective of "weak sustainability" under the RCP4.5 and RCP8.5 scenarios, respectively; (c) and (d) show the livestock supply under the "weak sustainability" objective under the RCP4.5 and RCP8.5 scenarios, respectively.

Table 6
The ecosystem services and their changing trends in different scenarios.

Grazing scenarios and objectives	Climate scenarios	NPP (kg C/ha)	SC (ton/ha)	WY (mm)	WR (mm)	Livestock supply (Million sheep)
UG	RCP4.5	3065	674	314	88	0
	RCP8.5	3235	1105	345	92	0
LG	RCP4.5	2886	681	318	88	21.55
	RCP8.5	3068	1140	345	91	22.06
MG	RCP4.5	2715	668	329	91	42.9
	RCP8.5	2911	1128	355	94	44.76
HG	RCP4.5	2512	667	344	96	64.7
	RCP8.5	2709	1113	368	98	66.38
Weak sustainability	RCP4.5	2882	691	330	93	23.5
	RCP8.5	3072	1151	358	96	22.8
strong sustainability	RCP4.5	2926	683	339	96	8
	RCP8.5	3083	1143	371	101	8.3
State of ecosystem services	RCP4.5 RCP8.5					

Note. UG: ungrazed, LG: lightly grazed, MG: moderately grazed, HG: heavily grazed, WS: weak sustainability, SS: strong sustainability. Please refer to the unit on the y-axis for the corresponding column headline.

natural resources and meet human need of livestock products.

The consideration of strong and weak sustainability in combination and integration with other techniques for development, such as spatially explicit landscape planning and management, would provide policymakers with more alternatives to formulate regional adaption schemes based on ecosystem service optimization under climate change and thus promote regional sustainable development.

6. Conclusions

Promoting the adaption of grassland ecosystems to climate change and meanwhile meeting the human demand for livestock products are a big challenge to achieve the goal of regional sustainable development in the arid and semi-arid areas. In this study, we developed a spatially explicit approach to identify the possible patterns, hotspots, and amplitudes of how the five items of ecosystem services (NPP, SC, WY, WR, and livestock supply) can be jointly impacted by future climate and grazing scenarios in the grassland and agro-pastoral transitional zone of China. On this base, we suggest appropriate grazing schemes corresponding to the objectives of "strong sustainability" and "weak sustainability", respectively. Under the "strong sustainability" objective, grazing should be limited in the north-central and west GAPTZ in the future climate scenarios, while under the "weak sustainability" objective, moderately grazing in the west and central parts and lightly

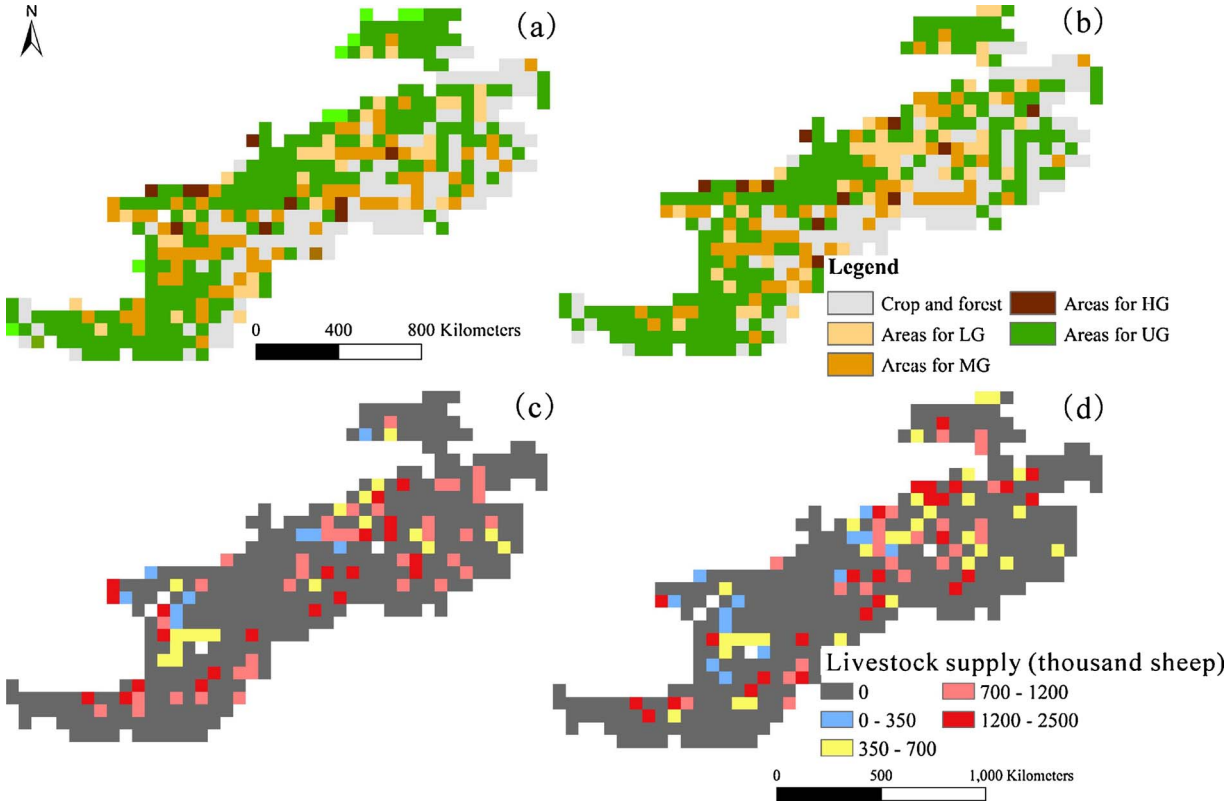

Fig. 10. (a) and (b) present the optimal grazing intensity based on the objective of "strong sustainability" under the RCP4.5 and RCP8.5 scenarios, respectively; (c) and (d) show the livestock supply under the "strong sustainability" objective under the RCP4.5 and RCP8.5 scenarios, respectively.

grazing in the other areas could be encouraged. In most areas of GAPTZ, HG would lead to grassland degradation and negatively affect overall ecosystem services greatly. Based on the principle of overall optimization, we can avoid the unnecessary tradeoff among different ecosystem services. Our study can provide policymakers with a spatially explicit paradigm to promote adaptation to climate change based on ecosystem service optimization.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.ecolind.2017.12.012.

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